Quarterly Progress Report

FAILURE CRITERIA FOR VISCOELASTIC MATERIALS

W. G. Knauss

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Firestone Flight Sciences Laboratory

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California Institute of Technology

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This report summarizes results obtained on the NASA Research Grant NGL-05-002-005, GALCIT 120, since September 1969. Some of these results pertain to analysis of tests on solid propellant fuel carried out prior to that date, but which are only now analyzed.

THE FUNDAMENTAL PROBLEM OF CRACK PROPAGATION

As we have stated in several past Quarterly Reports, we have considered the problem of a crack which propagates not in the direction of its own axis. ALL fracture analyses to date assume that the crack propagates along its axis although experimental evidence contradicts such an assumption. We have taken the solution for the problem in Figure 1 and ask the following question: If the crack extension length "a" is infinitesimal and ϕ is some non-zero angle, what will be the angle φ of crack extension? If we use the energy criterion that crack extension occurs whenever the maximum release equals the surface energy we are lead to co-linear crack propagation, i. e., $\varphi=0$ IN CONTRADICTION TO EXPERIMENT. Only in the case of loading normal or parallel to the crack do we observe agreement with experiment. These latter cases are those to which energy analyses have been applied.

We have arrived at a dilemma: Classical energy release calculation have been accepted on the basis of correlation with experiment. These classical problems considered only special crack geometries. We have now treated the general problem. It produces the same results for the special classical problems in agreement with experiment but not for any other geometries. There are two possible resolutions to this dilemma. First our calculations are not correct. In spite of repeated checks of algebra we continue to pursue this possibility because the second alternative is dismaying. This possibility states that the classical concept of crack growth on the basis of the energy criterion is not valid. This idea is so staggering that we cannot quite believe it. Today there are theories of crack growth which do not depend on energy criteria so that fracture mechanics is not deprived of its foundation. But some basic rethinking would have to be done to put the various aspects into new perspective.

For instance, one may interpret fracture growth more firmly in terms of the stress level at the tip of a crack. The same criterion would then be applicable to stress singularities WITHOUT cracks and thus free the mechanics of fracture from the hitherto absolutely necessary pre-existence of cracks.

CRACK PROPAGATION IN SOLID PROPELLANT

As stated in the last Quarterly Report we were awaiting shipment of propellant for crack propagation studies. This propellant (40 lbs.) has been received and machined into test specimens. Because this propellant is stronger than that previously tested some equipment modification is required, and this is underway. In order to make maximum use of the limited amount of propellant available we decided to photograph all tests. This requires high speed and low speed cameras. The high speed camera will be in use through December and the low speed camera will be repaired by then. Special precautions have been taken not to damage the specimens internally during handling.

INTERNAL FRACTURE AND DEWETTING OF PROPELLANTS

One objective of this year's effort was to demonstrate that relaxation in solid propellants is in substantial part due to internal cracking and dewetting.

We have calculated the response of a sheet of Solithane 113 as a model material which contains many little cracks when subjected to a constant strain. This situation corresponds to a relaxation test. In this particular case the bulk material is in its rubbery, relaxed state just like the rubber in propellants. The only time dependent process is crack growth. The result is shown in Figure 2.

We note that the slope of the apparent relaxation curve is about 1/4 of the log-log slope of the relaxation modulus of the polymer alone. Log-log slopes of 0.25 and less are a basic characteristic of propellants. Furthermore the relaxation times of the propellant are several orders of magnitude larger than those of the pure polymer. The same is true for propellants. N/A represents the density of initial flaws and $\overline{C}_o$ the average initial flaw size. $N\pi\overline{C}_o^2 = 0.5A$ corresponds roughly to saying that half the particles in a propellant are initially dewetted by a small amount. It is important to point out that the physics as well as the calculations for this type of relaxation process correspond to the propellant behavior.

There is a fundamental meaning to this as regards the constitutive behavior of propellants. If internal fracture accounts for a substantial part of propellant relaxation then permanent damage is done to the propellant for any straining. The material is not linearly viscoelastic but has permanent memory of past history. It follows that the stress strain behavior of such a material in a constnat strain rate test is as shown in Figure 3a, if the specimen is unloaded and then reloaded. This behavior is as observed on solid propellants. Details of this behavior are to be presented in a forthcoming paper.

We believe that the mechanics of internally fracturing solids describes with satisfactory consistency all the major deviations of propellant behavior from linearly viscoelastic behavior which we know today. In addition, this behavior incorporates as an integral part the cumulative damage of the material.

EXPERIMENTS ON PROPELLANT REGARDING CREEP AND RELAXATION

In order to translate the foregoing concepts into the behavior of actual propellants, creep tests have been constructed to determine the parameters which control the internal fracture history. We have measured the amount of creep as a function of stress level. A substantial portion of the test data shows such inconsistent results that the only explanation was specimen handling. Handling loads and strains of the thin specimens had preworked them so that some damage had been imparted. Since our theory predicts the continual presence of this damage in the stress-strain response it is only natural--on 20-20 hind-sight--that handling should introduce sizeable uncontrolled variations in the propellant response.

The creep compliance depends linearly on the number of growing defects. That number depends on the stress level because at a small stress only the larger defects grow while the initially smaller ones require a high stress. The number of active defects, therefore, depends on the stress. Figure 4 shows the increase of the number of defects with stress obtained for the JPL-ATS propellant. These defects were derived from those measurements which seemed to be reasonably consistent.

Second, it was observed that the rate of creep (log-log-slope of the creep compliance) increases with stress level. This is clearly so because the rate of cracking increases with stress level.

Typical data are shown in Figure 5. These data are needed to evaluate the stress strain law

$$\epsilon - \epsilon_{el} = \int_{o}^{t} \frac{N}{N_o} \left[\sigma(t, \tau)\right] \; c^2 \; \left[\sigma(t, \tau)\right] \frac{d\sigma}{d\tau} \, d\tau$$

$$\frac{dc}{d\tau} = f\left[\sigma(\tau)\right], \; c(o) = c_o$$

where ϵ_{el} is the purely elastic strain, probably negligible and c is the crack length of the micro cracks as a function of time. We are beginning to program the above equation for propellant materials. The objective is to demonstrate the material behavior for various strain and load histories and to generalize the uniaxial response to these dimensions and to compare these results with the actual measured response of the propellant.

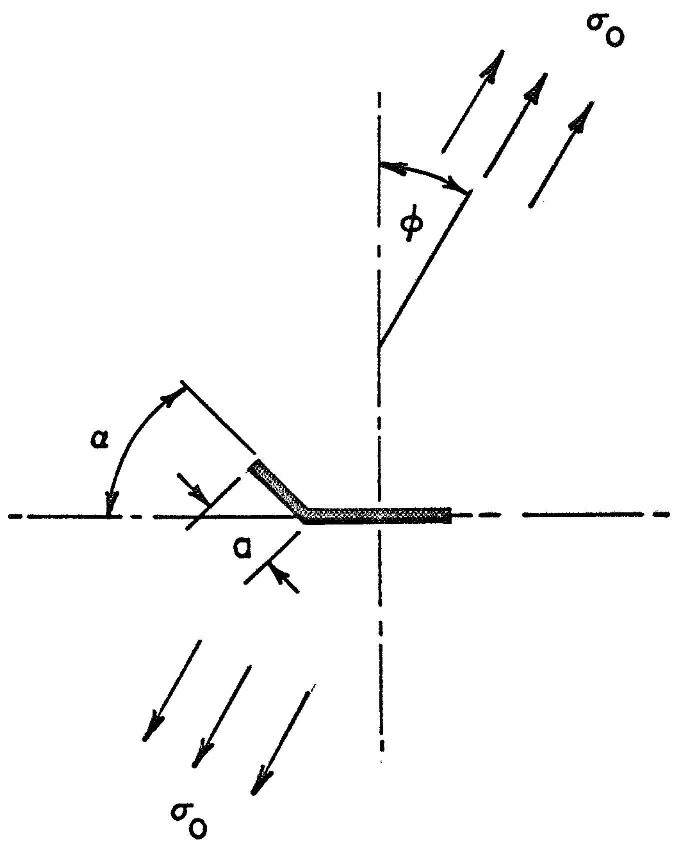

FIG. I CRACK AND LOADING GEOMETRY

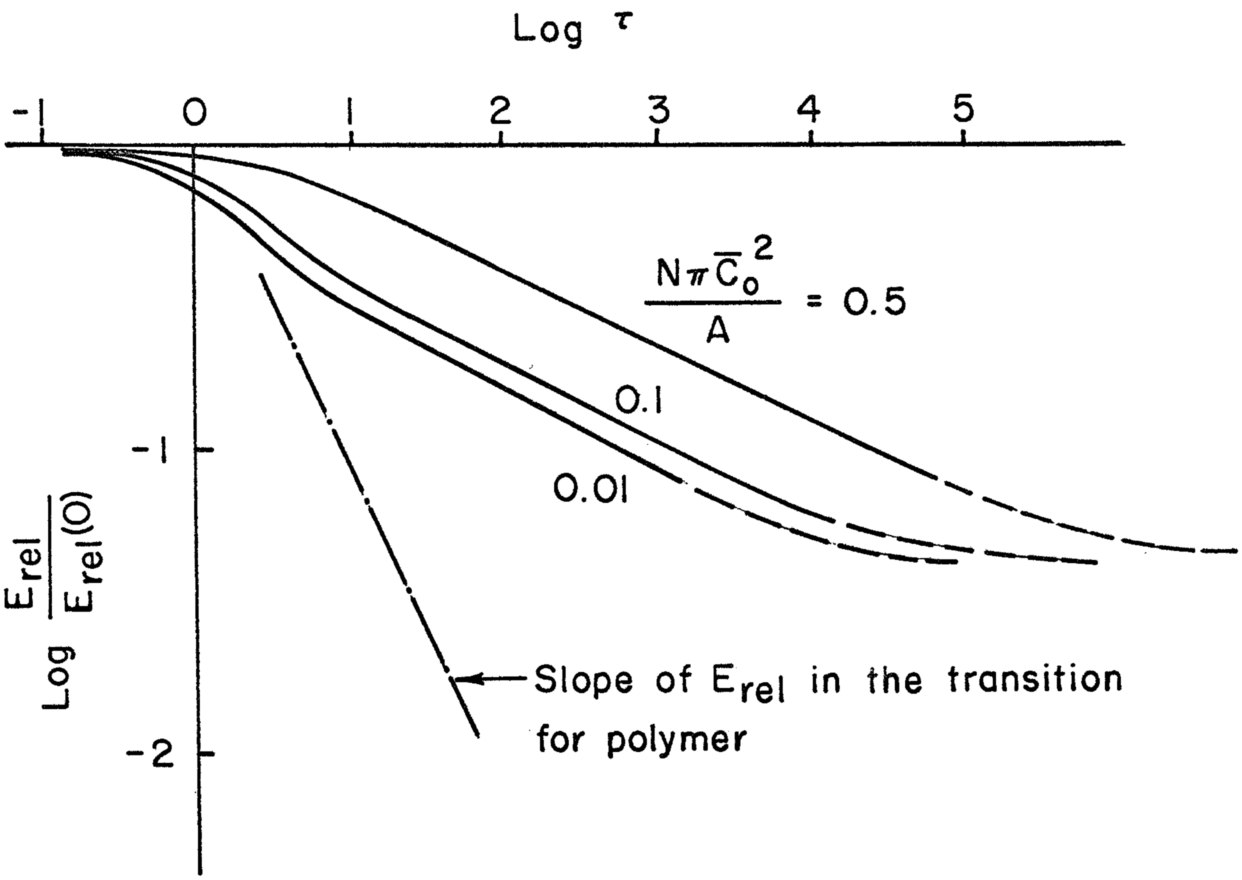
Log τ
-1
0
1
2
3
4
5
$\frac{N\pi\overline{C}_0^{\,2}}{A} = 0.5$
0.1
0.01
-1
-2
$\text{Log}\,\frac{E_{rel}}{E_{rel}(0)}$
Slope of E_{rel} in the transition for polymer

FIG. 2

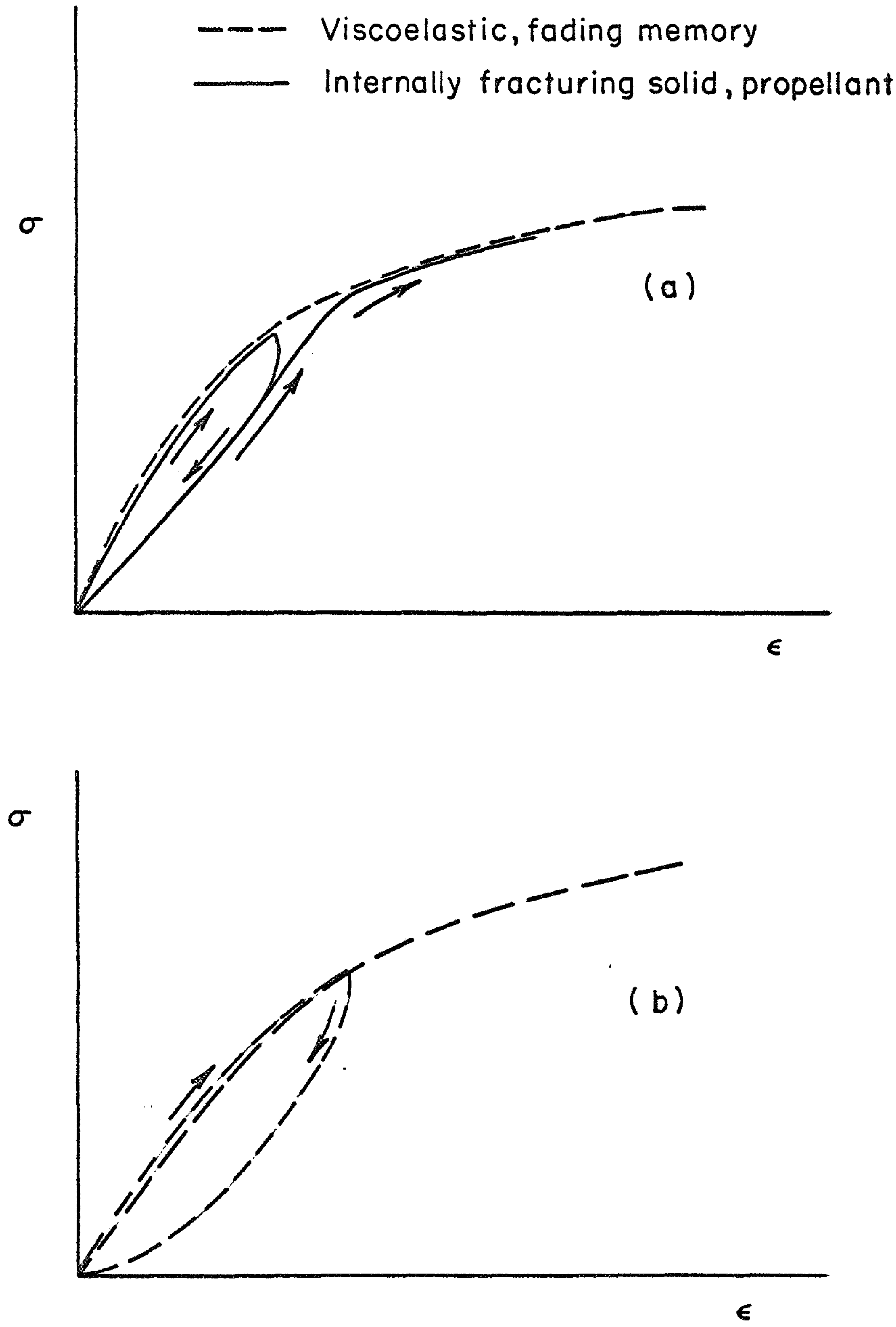

FIG. 3 DIFFERENCES IN MATERIALS WITH INTERNAL CRACK GROWTH (PERMANENT MEMORY OF DAMAGE) AND UNDAMAGED VISCOELASTIC SOLID

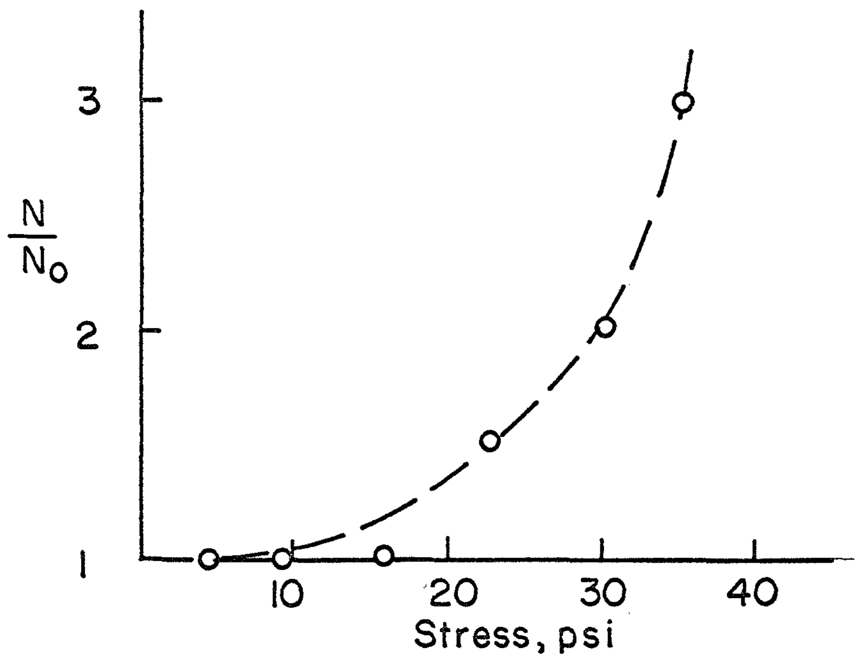

FIG. 4 NUMBER OF FLAWS ACTING AS A FUNCTION OF UNIAXIAL STRESS

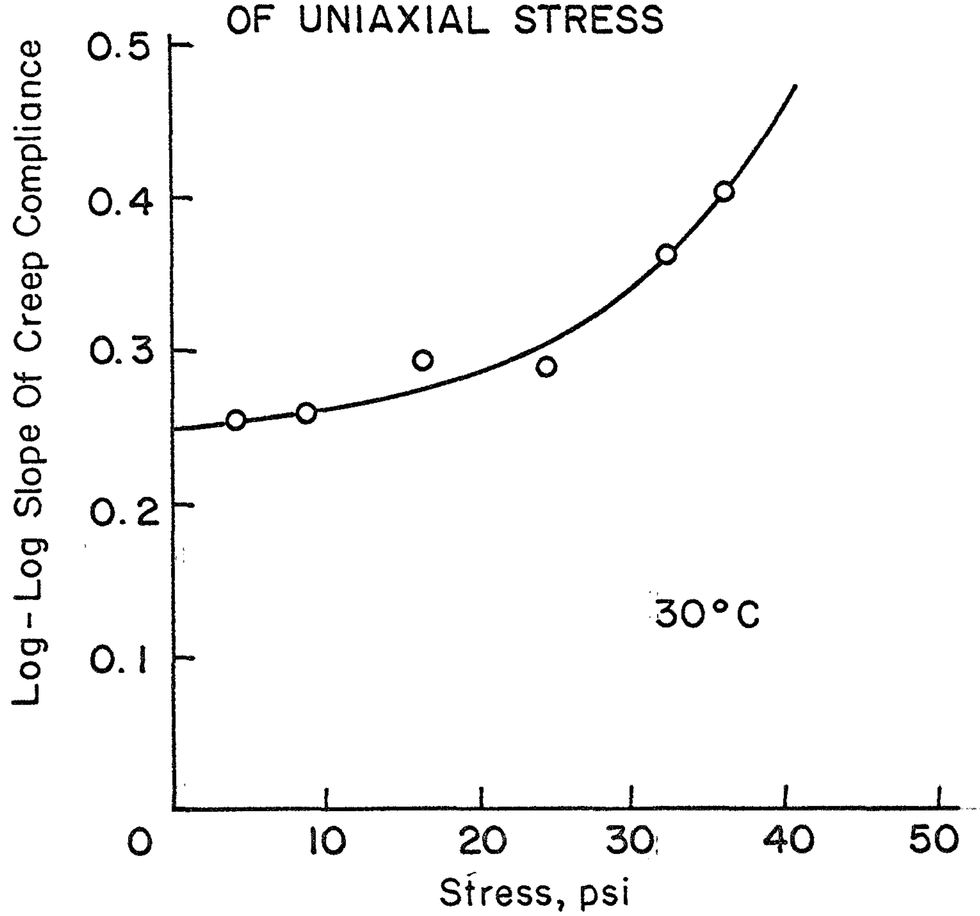

FIG. 5 SLOPE OF LOG D $_{CREEP}$ VS LOG TIME FOR DIFFERENT UNIAXIAL STRESS